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13. ABSTRACT *(Maximum 200 words)*

This project constituted an extensive program of research aimed at applying the techniques of Synchrotron White Beam X-ray Topography (SWBXT), Nomarski Optical Microscopy, Stereo Transmission Optical Microscopy and Scanning Electron Microscopy to the detailed analysis of defect structures in SiC crystals of various polytypes, and to determine how these defect structures can influence the performance of various kinds of device manufactured therein. It has served to establish a heightened awareness of the importance of a detailed understanding of growth defect microstructure to the future of SiC technology. Results obtained in this project have helped prioritize SiC crystal quality improvements. Two kinds of defect have been identified in 6H and 4H-SiC, basal plane dislocations, and dislocations with mostly screw component lying either at a small angle, or parallel, to the c-axis, with screw component of Burgers vector being equal to nc, where c is the lattice parameter. In 6H, dislocations with $b \geq 2c$ have hollow cores, the diameters of which conform to the theory of F.C. Frank. The same is true for dislocations in 4H with $b \geq 3c$. Preliminary results show that all such dislocations (from n=1 to n>8) can modify the I-V characteristics of diodes, giving rise to higher leakage currents and premature breakdown point-failures.

14. SUBJECT TERMS
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This project constituted an extensive program of research aimed at applying the techniques of Synchrotron White Beam X-ray Topography (SWBXT), Nomarski Optical Microscopy, Stereo Transmission Optical Microscopy and Scanning Electron Microscopy to the detailed analysis of defect structures in SiC crystals of various polytypes, and to determine how these defect structures can influence the performance of various kinds of device manufactured therein. It has served to establish a heightened awareness of the importance of a detailed understanding of growth defect microstructure to the future of SiC technology. The benefits of this heightened awareness to SiC technology are twofold: 1). Understanding the nature of the defects is a prerequisite for determining their origin in relation to the growth parameters. This can enable the development of strategies for modifying these growth parameters to eliminate or minimize the density of the various defects. 2). Understanding the influence of the various defects on device performance can help the crystal growers prioritize their efforts in defect reduction. This can also help the SiC community determine the degree to which the performance limits for the various classes of proposed device may be mediated by presence of the various defects.

Results obtained in this project[1-18] have helped prioritize SiC crystal quality improvements. Two kinds of defect have been identified in 6H and 4H-SiC, basal plane dislocations (generated by plastic deformation at the high growth temperature[1]), and dislocations with mostly screw component lying either at a small angle, or parallel, to the c-axis, with screw component of Burgers vector being equal to n*c*, where *c* is the lattice parameter. These latter dislocations are growth dislocations. In 6H-SiC, dislocations with $b \geq 2c$ have hollow cores, the diameters of which conform to the theory of F.C. Frank (F.C. Frank, Acta Cryst., 4, 497, (1951)). The same is true for dislocations in 4H-SiC with $b \geq 3c$. According to Frank, dislocations with Burgers vectors larger than some critical size are energetically favored to develop hollow cores; the energy required to form the inner-surface of the hollow core being less than the strain energy removed. Frank developed a thermodynamic relationship between core-radius and Burgers vector,

$$r_0 = \frac{\mu}{8\pi^2 \gamma} b^2$$

where μ is the shear modulus, and γ is the surface energy of the inner surface of the micropipe.

In recent research funded partly under this contract and by a subcontract from Cree Research Inc. (from a larger DARPA contract awarded to Cree) the relevance of this relationship to "so-called" micropipes in SiC was tested in detail. A technique for measurement of the Burgers vector of micropipes was developed which involved the measurement of the lattice tilt surrounding the dislocations using transmission geometry SWBXT of crystals cut parallel to the growth axis, which had part of the growth surface preserved along one edge.[13,15] This was extended into similar measurements using back reflection images recorded from the edge containing the growth surface. Nomarski optical microscopy images were used as a guide to enable imaging of the intersections of micropipes with this growth surface using SEM (back scattered electron mode). Micropipes were observed to form very broad but shallow craters at the surface which enabled unambiguous determination of their diameters at their points of intersection with these craters. One-to-one correlations were made between transmission and back reflection SWBXT images and both Nomarski and SEM images which enabled the Frank relationship to be directly tested. Detailed analysis indicated that a straight-line relationship existed between core-radius and the square of the Burgers vector, in agreement with the Frank relationship.[14,15,17] The slope of the graph of r_0 versus b^2 enabled the ratio of constants, γ/μ, to be determined.[15,17]

The impact of micropipes and 1*c* screw dislocations on the reverse-bias current-voltage (I-V) characteristics of 4H-SiC and 6H-SiC diodes was subsequently studied in collaboration with Dr. P. Neudeck at NASA Lewis Research Center.

Synchrotron White Beam X-ray Topography (SWBXT) was employed to map the exact locations of micropipes and 1*c* screw dislocations within SiC diodes in three separate sets of experiments. The first set of SWBXT images was recorded from the samples with both topside and backside aluminum contacts in place. The second set of SWBXT images was recorded after aluminum metallization had been stripped

from the samples. The third set of images was recorded following a lap and polish to remove polycrystalline SiC that deposited onto the wafer backside during epitaxial growth. This latter set yielded the clearest images, most distinctly revealing the locations of the defects.

The high-field reverse leakage and breakdown properties of these diodes were subsequently characterized on a probing station outfitted with dark box and video camera. Detailed comparisons of the I-V, SWBXT, and breakdown luminescence characteristics of dozens of devices on SiC wafers have been carried out to date.

Micropipe defects cause premature breakdown point-failures in SiC high-field devices fabricated in 4H- and 6H-SiC c-axis crystals. Visible microplasmas at micropipe locations were observed.

In devices without micropipes, $1c$ screw dislocations degrade the reverse leakage and breakdown properties.[18] Devices that contained at least one $1c$ screw dislocation exhibited a 5% to 35% reduction in breakdown voltage, higher pre-breakdown reverse leakage current, a softer breakdown I-V knee, and visible microplasmas in which highly localized breakdown current was concentrated. The locations of observed breakdown microplasmas corresponded exactly to the locations of $1c$ screw dislocations identified by SWBXT mapping. Most devices without screw dislocations exhibited excellent characteristics, with no detectable leakage current prior to breakdown, a sharp breakdown I-V knee, and no visible concentration of breakdown current.[18]

Positive temperature coefficient of breakdown voltage was found in 4H-SiC diodes without micropipes (P. Neudeck and C. Fazi, IEEE Electron Device Letters, 18, 96-98, (1997); H. Mitlehner, W. Bartsch, M. Bruckmann, and K. O. Dohnke, and U. Weinert, in Proc. IEEE Int. Symp. On Power Semiconductor Devices and IC's, May 1997, pp. 165).

There are several possible mechanisms for localized breakdown which might be applicable to the super screw dislocation breakdown in SiC. First, lattice deformation around a screw dislocation changes the semiconductor band structure in the vicinity of the defect. This leads to a local reduction in the SiC bandgap and carriers would require slightly less energy to impact ionize, which increases the probability of breakdown due to carrier tunneling. Second, the presence of dangling bonds down the core of the screw dislocations may also play a role in the defect-assisted breakdown process. Also, enhanced impurity incorporation may arise as the $1c$ screw dislocation propagates during epilayer growth, which would result in higher doping or deep level impurities near the dislocation that would locally reduce breakdown voltage.

Further studies are underway to better quantify the impact of screw dislocations on the electrical properties of SiC power devices.

Publications Acknowledging ARO Support Over Duration of Contract

a. Theses

1. S. Wang, "Characterization of Growth Defects in Silicon Carbide Single Crystals by Synchrotron X-ray Topography", Ph.D. Thesis, Stony Brook, (1995).

2. W. Huang, "Computer Aided Synchrotron White Beam X-ray Topographic Structural and Microstructural Analysis of Semiconductor Devices", Master's Thesis, Stony Brook, (1997).

b. Refereed Articles

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List of Reportable Inventions

None